Effects of biochar on cement stabilised peat soil

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Abstract

Peat is a soft soil with very high organic content, which makes it highly susceptible to extreme differential settlement. Although cement stabilisation is highly effective, it is not a common practice due to the high cost of treatment associated with large amount of binder dosage. In this paper, the use of a novel material, biochar as a potential replacement for cement and as an alternative filler to sand, was investigated. Biochar is more sustainable than traditional construction materials and has carbon sequestration ability. It could potentially be cheaper than cement or sand, depending on the source of feedstock used. Cement treated peat with sand was used as a benchmark to assess the performance of biochar enhanced cement treated peat. The samples with biochar finer than 75 μm performed better than sand equivalent, over 50 % increase in compressive strength. Furthermore, it was found that the samples with 100 $\mathrm{kg/m^3}$ cement and 400 $\mathrm{kg/m^3}$ biochar had comparable performance to the control sample with 200 $\mathrm{kg/m^3}$ cement only, without biochar, highlighting the potential of biochar to partially replace cement. Scanning Electron Microscopy and X-ray Diffraction tests results showed that the mechanisms behind the performance gain in biochar samples are of both mechanical and chemical nature.

1 Introduction

Peat soil is a type of soft soil with very high organic content, typically over 75 %, which consists of partially or completely decomposed organic matters in a water saturated environment. Peat typically lacks any kind of substantial soil structure and is extremely compressible. These physical characteristics of peat are highly undesirable for construction due to the potential for large differential deformations. Chemical stabilisation is often used to treat soft soils, usually with a high degree of success. When chemical binders such as dry cement are added to soil in the presence of water, cementitious and/or pozzolanic reactions occur to form cementitious gels, which contribute to the increase in strength of the soil matrix. However, the presence of organic matters in peat is expected to inhibit or slow these reactions (Tremblay *et al.*, 2002). As a result, a large quantity of binder is required before a significant strength gain is observed (Janz and Johansson, 2002).

Fillers such as sand are typically introduced into the stabilisation mixture to reduce the binder quantity required. However, sand is a finite resource and the global demand for construction sand has put a massive strain on already depleting reserves. This paper aims to investigate an alternative filler, biochar, as a replacement for sand. Biochar is a product of pyrolysis where biomass is subjected to a high temperature in the absence of oxygen. The thermal decomposition process at high temperature prevents the biomass from disintegrating into ash but instead creates a porous honeycomb like cell structure. Biochar has no cementitious properties but has very high water holding capacity due to the abundance of cells (micropores) developed during the pyrolysis process.

Biochar has recently gathered interest in the field of land remediation for treating contaminated soils and in the agricultural sphere, where a significant increase in productivity for different types of crops has been documented (Lehmann and Joseph, 2009). Biochar feedstock can be categorised into two groups, biomass and waste biomass (Brick and Lyutse, 2010). Conventional biomass includes grass, soft and hardwood and algae grown specifically for biochar production, while biomass wastes include agricultural wastes, forestry residues, used tyres, old building materials, municipal solid wastes, and other (Brewer, 2012). Waste biomass has a clear advantage over conventional biomass as the inherent cost of producing biochar is significantly reduced since waste biomass is typically synonymous with cheap or free feedstock which could potentially make biochar cheaper than cement or sand. In addition to that, biochar is also considered carbon negative and has the potential for carbon sequestration, which further adds to the benefit of using biochar in ground improvement efforts for peat soil. This paper explores the potential use of biochar to partially replace cement and sand filler.

2 Materials

2.1 Peat

The natural peat in this study was obtained from a local garden center, sourced from Irish bogs owned by the Bord na Mona company. The Irish Moss Peat used in the experiment is classified as brown, with a moderately strong humification, H6 on the von Post scale (Hartlén and Wolski, 1996; Hobbs, 1986) and contains a considerable amount of amorphous material. It also has a moderate smell, no plasticity, and no tensile strength. The pH of the peat was evaluated by combining air dried and sieved peat with deionized water at 1:5 ratio and leaving the mix to stand for 1 hour before measurement. The peat is acidic with a pH level of 3.6. The water content was evaluated using an oven temperature of 110 °C and following the standard test method for moisture content of peat, ASTM D2974 (ASTM, 2014a). Typically, the store bought peat is air-dried after harvesting to remove excess water and then bagged to be sold commercially. Therefore, the water content determined in the laboratory is not truly representative of the natural water content of the peat. The store bought peat had an average water content of 165 %.

A review conducted by Huat (2004) showed that the natural water content of peat is highly variable, between 115 % to 2,000 % depending on the location and the formation of the peat bogs. Previous investigation by Hernandez-Martinez (2006) concluded that the higher the water content of peat, the lower the compressive strength of the cement stabilised peat. In this investigation, the peat was reconstituted to a relatively high water content of 1,000 % to further accentuate the effects of adding biochar to the stabilisation mixture. The peat reconstituted to 1,000 % water content had a bulk density of 976 $\mathrm{kg/m^3}$.

2.2 Ordinary Portland cement

Ordinary Portland cement (OPC) is the most commonly used binder for peat soil stabilisation and also the most effective (Janz and Johansson, 2002).The cement is a Class 52,5R CEM I Ordinary Portland Cement and meets the requirements of EN 197-1:2011. The chemical composition provided by the manufacturer is shown in Table 1.

2.3 Biochar

The biochar used in this experiment, produced by BioRegional, is derived from mechanically chipped trunks and large branches of *Fraxinus excelsior I.*, *Fagus sylvatica I.*, and *Quercus robur I.*, pyrolysed at 450 °C for 48 hours (Jones *et al.*, 2011). These hardwood timbers were sourced from Forest Stewardship Council (FSC) certified and sustainably managed UK woodlands. Typical physical and chemical properties of the

Components	(%)
Portland cement clinker	90 - 95
Limestone/shales	0 - 5
Calcium sulphate	0 - 5
Tin sulphate	< 1
Ferrous sulphate	< 1

Table 1: Typical chemical composition of cement

Properties	Parameter Value
Moisture content (%)	3.5
pH	8.1
Electrical conductivity (μS cm^{-1})	1133
Total C (%)	76.1
Total N (%)	6.8
C-to-N ratio	112
Water holding capacity (%)	97.7
Specific surface area (m^2 g^{-1})	39.0

Table 2: Typical physical and chemical properties of BioRegional biochar (Jones *et al.*, 2011)

biochar are shown in Table 2. The pH of the biochar powder was measured by adding 100 mL of deionised water (10 % w/w) to 10 g of biochar and leaving the mix to stand for 24 hours. The pH of the suspension was measured to be 8.1. The biochar was crushed and sieved into five different ranges of particle sizes. A summary of the five ranges of particle sizes is shown in Table 3.

2.4 Sand

Typical building sand and some fine silica sand were combined and screened into the same five ranges of particle sizes as biochars, as shown in Table 3.

3 Experimental program

Experiments were conducted on peat reconstituted to a water content of 1,000 %. Dry cement binder, biochar, and sand were all added to the peat soil as a percentage of the weight of the wet peat which is representative of the industry's practice. A summary of the mixture proportions is shown in Table 4. Hereon, cement

Grain Size	Biochar/Sand	Particle Size Range
Coarse	A	2.0 mm - 5.0 mm
Medium	B	425 µm - 2.0 mm
Fine	C	250 µm - 425 µm
Very Fine	D	75 µm - 250 µm
Extremely Fine	E	$<$ 75 µm

Table 3: Particle size ranges for sand and biochar

Binder Quantity (kg/m^3)		
Cement	Biochar	Sand
100	0	0
150	0	0
200	0	0
100	100	0
100	200	0
100	300	0
100	400	0
150	100	0
150	200	0
150	300	0
150	400	0
200	100	0
200	200	0
200	300	0
200	400	0
200	0	200

Table 4: Binder mixture composition

stabilised peat samples with sand will be referred to as sand samples and cement stabilised peat samples with biochar added as biochar samples.

3.1 Sample preparation

Before the samples were created, five bags of peat were mixed to ensure homogeneity. The peat was then screened using a 5 mm sieve to remove any large debris, including gravel and large branches. For each batch of samples prepared, the water content of peat was determined as per ASTM D2974 (ASTM, 2014a) to ascertain the amount of additional water required to bring water content to 1,000 %. Biochar was crushed and sieved into five different ranges of particle sizes labeled A to E, for decreasing particle sizes (Table 3). Similarly, the sand was divided into five groups with the same ranges of particle sizes as the biochar. The crushed biochar was dried in an oven at a relatively low temperature of 50 $^{\circ}\mathrm{C}$ for 24 hours to remove moisture absorbed during storage while preserving the integrity of the porous cell structure. The graded sand was dried in the same condition.

First, a measured amount of tap water was added to the peat using a paddle paint mixer on medium speed for five minutes. Then, depending on the batch of samples prepared, either sand or biochar were added according to the mixture proportions shown in Table 4, followed by five minutes of mixing. The dry cement was added and the resulting material was mixed continuously for another five minutes. Prior to filling, each PVC mould was lightly coated with silicone grease to assist with the de-moulding process of the samples after curing. The treated peat was then spooned into 70 mm diameter PVC split moulds carefully in five layers. After each layer, a bent fork was used to press down the top of the layer five times and then tamped ten times using a 40 mm diameter solid cylindrical aluminum rod, weighing 600 g. The sample preparation technique was considered to be reliable with coefficient of variations of dry density between 0.6 and 5 % across all samples. The samples were then cured in a water tank at room temperature in an environment

with relative humidity higher than 90 %. The samples were permitted to absorb water from both ends of the mould. The samples were cured for 7 and 28 days, with some selected samples cured for longer, 60 and 120 days, respectively.

3.2 Unconfined compression test

Unconfined compression tests (UCS) were conducted to measure the compressive strength of the stabilised samples. The tests were conducted in accordance with ASTM D2166 (ASTM, 2013).

The unconfined compression strength of the samples was measured using a universal automatic compression testing machine manufactured by Controls Group, fitted with a 2.5 kN load cell. The load was applied to the samples at a constant rate of 1.07 %/min until the samples reached an axial strain of 10 %. All 7 and 28 days samples were tested in triplicates to ensure the results to be statistically significant. Fewer specimens were available for curing times of 60 and 120 days.

The samples were gently released from the PVC moulds and then trimmed to size ensuring a height-to-diameter ratio of between 2.0 and 2.5. Three measurements of height and diameter were taken to determine the bulk volume of the samples and were on average 140 mm and 70 mm, respectively. The samples were weighed before testing to calculate the wet density. The water content of the samples was determined in accordance with ASTM D2974 (ASTM, 2014a). A pre-load of 5 kPa was applied at the start of each test to ensure the top platen was in full contact with the top of the samples and loading was applied uniformly. Area correction was applied to all the results as per ASTM D2166 (ASTM, 2013).

3.3 Scanning electron microscope

Scanning electron microscopy (SEM) tests were only conducted on biochar samples of five different particle sizes and the control sample, all cured for 7 days as the compressive strength showed the greatest variation at this time. A ThermoFisher/FEI Quanta 600 equipped with a dedicated backscatter detector and an SDD EDS detector was used. A more detailed sample preparation and analyses can be found in Berti et al. (2018). The purpose of SEM imaging was to help with the understanding of the microstructure of the stabilised peat soil and to observe the effects of the addition of biochar, including any effects of the sizes of biochar.

3.4 X-ray powder diffraction

X-ray powder diffraction (XRD) tests were carried out on the same samples used for SEM tests using a Siemens D500 diffractometer. Additional XRD tests were acquired from samples with size E biochar, cured for a longer period, 28 and 120 days, respectively using a Bruker D8 Advance diffractometer. The samples were scanned between 3 and 65° 2θ, at steps of 0.05° 2θ and 4 sec/step counting time. The purpose of conducting XRD was to better understand the changes in chemical composition due to the inclusion of biochar, including effects of biochar particle size and sample curing period.

4 Results

The results of the investigation can be broadly summarised into three phases. Firstly, the effects of the different biochar and sand particle sizes on cement stabilised peat are presented. The compressive strength results from sand samples were used as a benchmark to assess the performance of biochar samples. The effects of curing period were also included. In the second phase, the mechanisms of interaction between biochar, peat, and cement are explained using the results from SEM and XRD tests. And finally, the effects of a different combination of cement and biochar quantities are presented to explore the optimal combination. Only size E biochar (finer than 75 µm) was used in the final set of experiments.

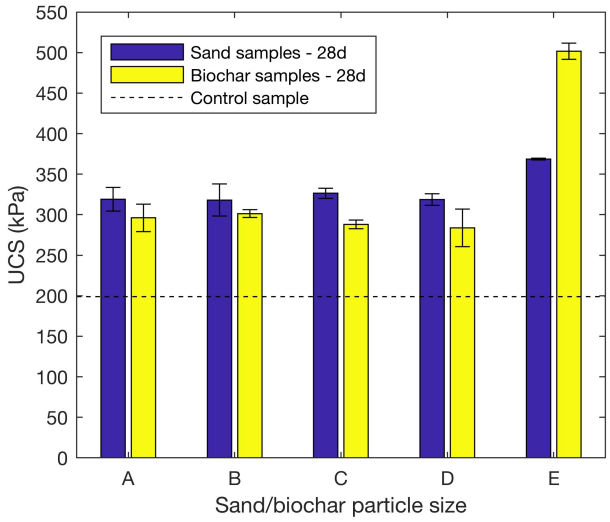

Figure 1: Effects of particle size on UCS of cement stabilised peat after 28 days curing (200 $\mathrm{kg/m^3}$ cement, 200 $\mathrm{kg/m^3}$ sand or biochar; control with 200 $\mathrm{kg/m^3}$ cement only)

4.1 Phase 1 - Performance of cement stabilised peat with sand or biochar filler

4.1.1 Effects of sand filler

The first set of tests was carried out on the peat treated with 200 $\mathrm{kg/m^3}$ of both cement binder and sand and cured for 28 days. These results were used as a benchmark to evaluate the performance of biochar samples. Figure 1, 2, 3 and 4 show the effects of particle size of sand and biochar on unconfined compressive strength (UCS), dry density, void ratio and water content, respectively for cement stabilised peat cured for 28 days. An increase in compressive strength was observed (Figure 1) when sand was added to the stabilisation mix, irrespective of the sand particle sizes, which is consistent with findings of previous research (EuroSoilStab, 2001). The variability in strength between sand particle sizes A to D is almost indistinguishable but samples with size E sand are appreciably stronger than the rest, recording an average peak strength of 369 kPa. Similar findings were reported by Dehghanbanadaki *et al.* (2013) where fine poorly graded sand performed much better than coarse poorly graded sand when mixed with peat and cement binder. The inclusion of sand increases the number of particles available to act as bridges for hydration products, therefore increasing the strength of the soil matrix. The additional particles help with the cementation by binding soil particles with sand particles together at their contact points (Kézdi, 1979). The finest sand particles have the highest surface area for a given weight, therefore allowing for more contact points between sand and soil particles. This encourages more spot welding to happen, resulting in a stronger load bearing soil matrix. A similar phenomenon was observed in investigations conducted by Christopher *et al.* (1989) and Ismail *et al.* (2002) on chemically cemented sand where finer sand particles always yielded higher strength.

Higher strength was coupled with the distinct increase in dry density and a decrease in void ratio of all the sand samples compared to the control sample (Figure 2 and 3). The void ratios among sand samples were fairly uniform, evidence of a consistent sample preparation methodology. It was also found that the inclusion of sand reduced the water content of the samples as shown in Figure 4. However, given that sand does not react with water, it is likely that the reduction in water content is due to water being displaced by sand grains.

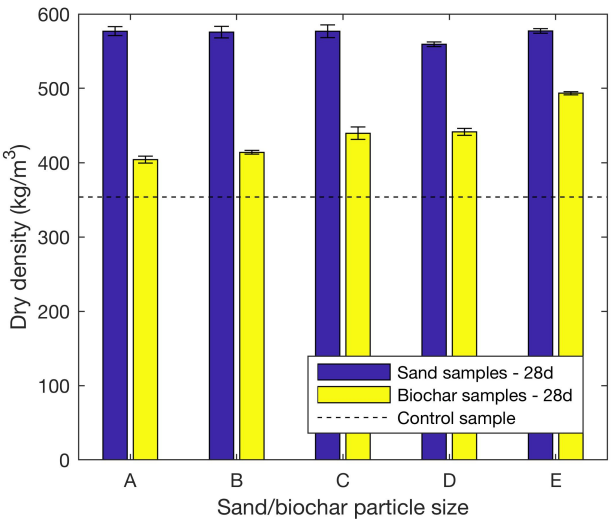

Figure 2: Effects of particle size on dry density of cement stabilised peat after 28 days curing (200 $\mathrm{kg/m^3}$ cement, 200 $\mathrm{kg/m^3}$ sand or biochar; control with 200 $\mathrm{kg/m^3}$ cement only)

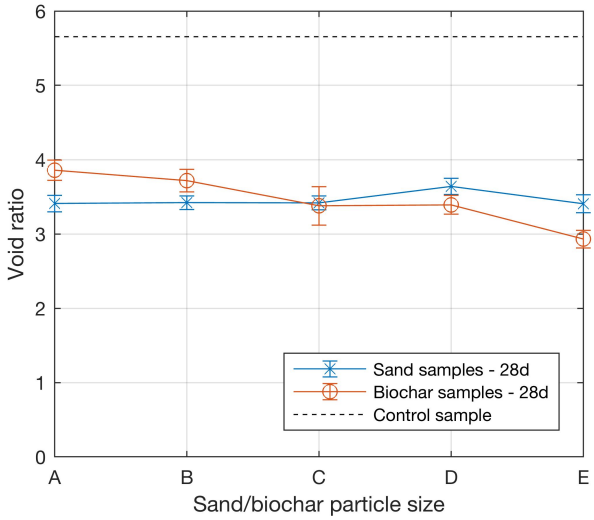

Figure 3: Effects of particle size on void ratio of cement stabilised peat after 28 days curing (200 $\mathrm{kg/m^3}$ cement, 200 $\mathrm{kg/m^3}$ sand or biochar; control with 200 $\mathrm{kg/m^3}$ cement only)

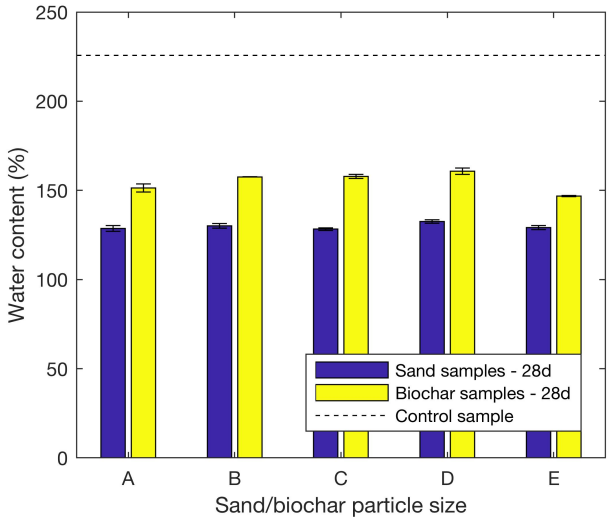

Figure 4: Effects of particle size on water content of cement stabilised peat after 28 days curing (200 $\mathrm{kg/m^3}$ cement, 200 $\mathrm{kg/m^3}$ sand or biochar; control with 200 $\mathrm{kg/m^3}$ cement only)

4.1.2 Effects of biochar

The samples prepared for this experiment had 200 $\mathrm{kg/m^3}$ cement and 200 $\mathrm{kg/m^3}$ biochar and were left to cure for 28 days. The inclusion of biochar in cement stabilised peat also had a positive impact on the compressive strength of the samples, resulting in strengths consistently higher than the control sample, irrespective of the particle sizes of biochar (Figure 1). The performance of biochar enhanced cement stabilised peat after 28 days of curing was almost comparable to that of sand samples, albeit slightly weaker. However, there was a notable difference in performance when the average particle size of biochar was finer than 75 $\mu\mathrm{m}$ (size E). The size E biochar samples had the highest overall strength at 502 kPa which is approximately 170% stronger than the average strength of the other biochar samples and about 35 % stronger than cement stabilised samples with size E sand, partly due to the lower void ratio for size E biochar sample compared to the sand sample equivalent as shown in Figure 3. Biochar has considerably lower specific gravity compared to sand grains: G_s of biochar is 0.9-1.2 (Yargicoglu *et al.*, 2015) vs 2.6-2.7 for sand. Therefore, for the same weight of filler added, a larger volume of biochar (higher number of biochar particles) was added to the mixture compared to sand. It is therefore expected that the void ratio for biochar samples to be lower than that of sand samples. The higher void ratios of size A and size B biochar samples was most likely due to the presence of empty cells found within biochar particles. Further discussion of the effects of the microstructure will be detailed in the next phase using SEM micrographs.

Biochar also has a much higher water absorption capacity (Zhang and You, 2013) compared to sand. Therefore, it was also observed that biochar samples consistently retained more water compared with the sand samples as evidenced by the higher water content, on average 19.4 % higher across all five ranges of particle sizes as shown in Figure 4. During the formation of calcium silicate hydrate ($C-S-H$) gels, the coating around the unhydrated cement makes it increasingly difficult for the water to reach the unhydrated cement and the rate of reaction is essentially controlled by the rate of diffusion of water through the $C-S-H$ layer. Therefore, the water saturated biochar fragments distributed throughout the samples could potentially allow for water to be more accessible for higher degree of hydration. SEM tests were conducted to investigate the homogeneity of the biochar fragments and hydration products distribution. Furthermore, XRD tests were conducted to quantify the increase in hydration.

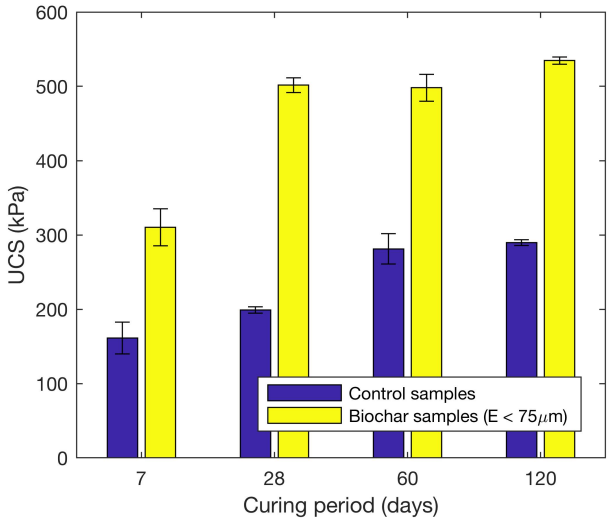

Figure 5: Effects of curing period on UCS of biochar samples compared with control sample (200 $\mathrm{kg/m^3}$ cement and 200 $\mathrm{kg/m^3}$ biochar; control with 200 $\mathrm{kg/m^3}$ cement only)

4.1.3 Effects of curing period for biochar samples

Selected biochar samples (200 $\mathrm{kg/m^3}$ of both cement and size E biochar, finer than 75 $\mu\mathrm{m}$) were cured for 7, 28, 60 and 120 days to investigate the effects of curing period on UCS, dry density and water content (Figure 5, 6 and 7). Both biochar and control samples showed an increase in strength with curing period (Figure 5), which is consistent with the understanding of continued hydration with time as long as the samples have enough moisture and unhydrated cement. The inclusion of biochar increased the rate and degree of hydration of cement in the stabilised peat samples as biochar samples gained more strength after 28 days compared to control sample. The effects of curing period were minimal on the dry density and water content of all the stabilised peat samples and are considered negligible (Figure 6 and 7).

4.2 Phase 2 - Microstructure and chemical composition

Scanning electron microscopy (SEM) and X-ray powder diffraction (XRD) tests were conducted to further facilitate the understanding of the hydration mechanisms of cement stabilised peat with added biochar. Texture and microstructure can be observed using SEM, while XRD can quantify and qualify the changes to the sample's chemical composition. SEM tests were only conducted on biochar and control samples cured for 7 days as it was observed that the compressive strength of samples with different biochar particle size showed the greatest difference. XRD tests were conducted on the same set of samples, with additional tests conducted on size E biochar samples cured for longer periods, 28 and 120 days. All the biochar samples had 200 $\mathrm{kg/m^3}$ cement and 200 $\mathrm{kg/m^3}$ biochar, while the control samples were treated with only 200 $\mathrm{kg/m^3}$ of cement.

4.2.1 Results from SEM

Biochar fragments used in this experiment are easily identifiable in SEM micrographs by their cellular structure with straight walls and rigid structure as shown in the air-dried sample captured in secondary mode (SE) (Figure 8). A snapshot of the polished resin embedded biochar samples analysed in backscatter mode (BSE) shows the honeycomb structure of biochar (Figure 8c). The micrograph shows the cells have an average

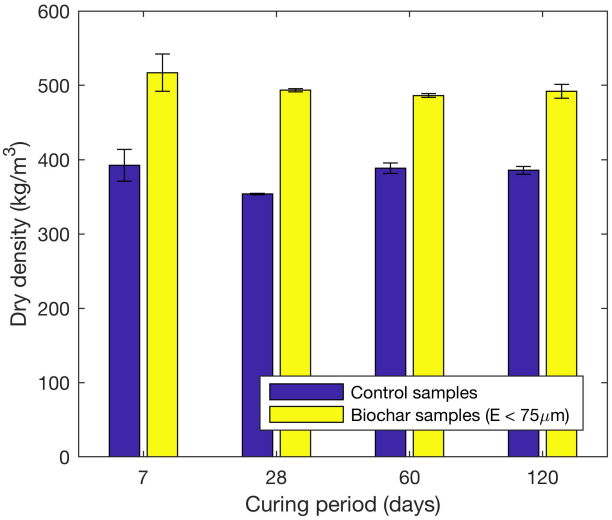

Figure 6: Effects of curing period on dry density of biochar samples compared with control sample (200 $\mathrm{kg/m^3}$ cement and 200 $\mathrm{kg/m^3}$ biochar; control with 200 $\mathrm{kg/m^3}$ cement only)

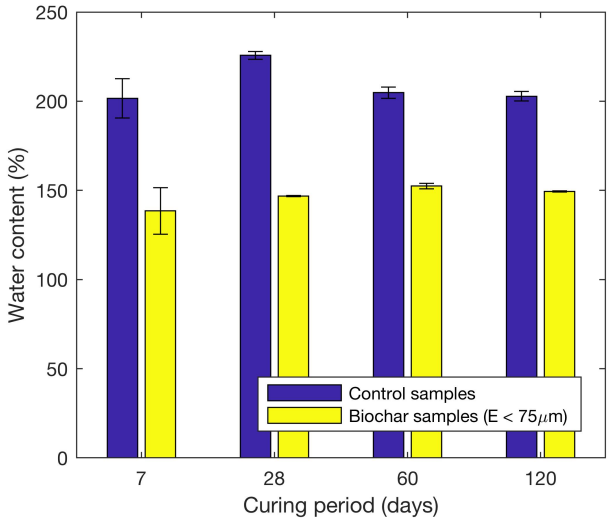

Figure 7: Effects of curing period on water content of biochar samples compared with control sample (200 $\mathrm{kg/m^3}$ cement and 200 $\mathrm{kg/m^3}$ biochar; control with 200 $\mathrm{kg/m^3}$ cement only)

diameter of 10 μm and a length between 10 and 100 μm. Peat particles are heterogeneous in shape and size and appear as flexible porous ribbons. $C-S-H$ and ettringite are two of the main hydration products of cement and have a characteristic morphology that makes them easily identifiable by SEM. $C-S-H$ forms a fuzzy, sponge-like coating around particles, while ettringite forms needles up to 10 μm long and tends to aggregate in a random orientation (Figure 8b).

The SEM-BSE micrographs (Figure 9) show that size A to size D biochar fragments had largely intact cells with cement hydration products formed around the biochar. The cells were filled with hydration products to a varying degree but mostly concentrated on the outer layers, while the inner layers were predominantly empty. In samples with size E biochar, the fragments did not preserve intact cells. The empty cells can become weak zones, providing an additional reason samples with size A to size D biochar were not as strong as samples with size E biochar. This also explains the higher void ratios of size A and B biochar samples observed in Figure 3. Similar hydration products were seen in all samples but the distribution of the hydration products was more homogeneous in samples with size E biochar. The lack of intact cells and the much more homogenous distribution of hydration products in samples with size E biochar are the two main reasons for the distinctively higher compressive strength obtained.

4.2.2 Results from XRD

Figure 10 shows the XRD patterns of biochar samples with different particle sizes and the control sample after 7 days of curing. The XRD patterns showed relatively similar reflections at similar 2θ angles and overall similar features. However, the presence of amorphous materials, like peat and biochar, add diffused reflections, which tend to obscure the peaks of other minerals, further increasing the complexity of the patterns. Calcite, portlandite ($CaOH$), and C_2S account for the most intense and narrow peaks in the pattern (Figure 10). Portlandite is a common hydration product from C_3S which occur in the early stages of hydration. The absence of C_3S and C_3A peaks from the XRD patterns indicate the completion of the first phase of cement hydration, while C_2S peaks are clearly evident because C_2S reacts more slowly than C_3S and is responsible for the strength of mature cement paste (Jennings and Thomas, 2009). The presence of calcite also indicates that carbonation is also taking place, in addition to the usual hydration. During carbonation, portlandite reacts with CO_2 to form calcite and water. The generally higher intensity of the peaks of calcite and portlandite for biochar samples is also indicative that more hydration has occured, which supports the higher compressive strength observed in biochar samples over the control samples. Ettringite peaks could not be identified from the XRD pattern despite the clear evidence of its presence from the SEM micrographs. The absence is likely due to the attenuating effects of the amorphous materials like peat and biochar combined with ettringite's low degree of crystallinity.

A Rietveld refinement was conducted on the XRD data to quantify the crystalline phases present in each of the specimen. The process involved simulating the overall pattern of the mixture of minerals found in the biochar-cement stabilised peat by modelling each component based on their atomic structure as well as the effect of the instrument. Table 5 shows the simulated main mineral structures and the results of the quantification normalized to the crystalline fraction at 7 days curing. Generally, the variation of the percentage of different crystalline phases identified was much more prominent between the control and biochar samples. Cellulose is identified as the primary crystalline component of biochar. There is a notable decrease in portlandite content in all the biochar samples compared to the control (except for sample with size D biochar) confirming that portlandite was consumed in the process of carbonation to produce calcite. C_2S content also decreased in samples with biochar for all biochar sizes compared with the control, which indicates that more hydration has occurred. This correlated with the higher compressive strength observed in the biochar samples compared to the control. However, the quantitative Rietveld analysis of the XRD results was not able to provide further justification of the variation in strength between the samples with different biochar particle sizes to be linked to the variation in total amount of hydration products.

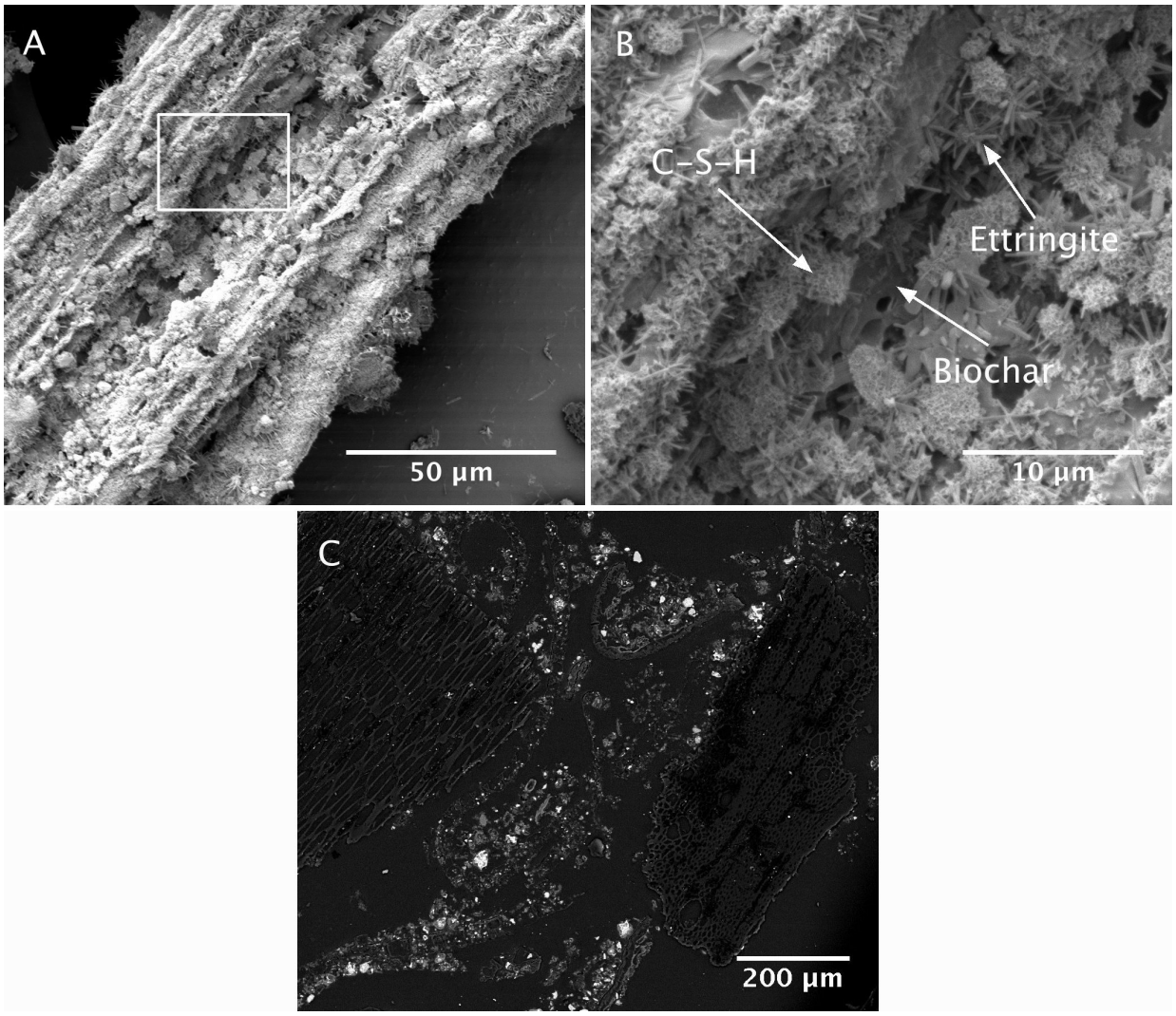

Figure 8: Cement hydration on biochar surface. A: Air-dried sample showing a typical biochar fragment, identified by its straight and rigid structure, coated with cement hydration products. B: Magnified view of $C-S-H$ morphology and the ettringite formation. C: Polished resin embedded sample showing the honeycomb structure of biochar.

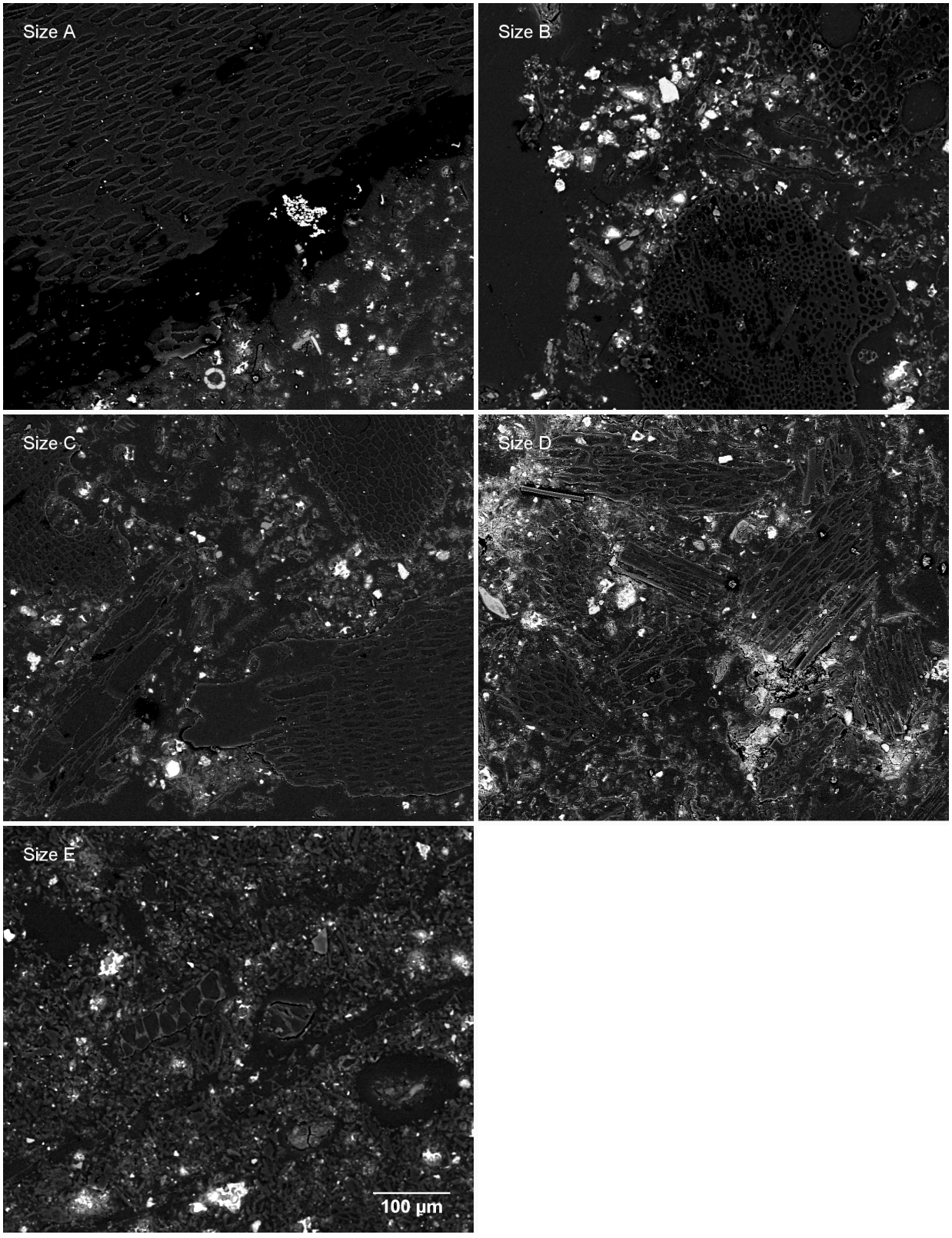

Figure 9: SEM-BSE micrographs of polished resin embedded biochar samples with different sized biochar fragments showing largely intact biochar fragments except for size E biochar.

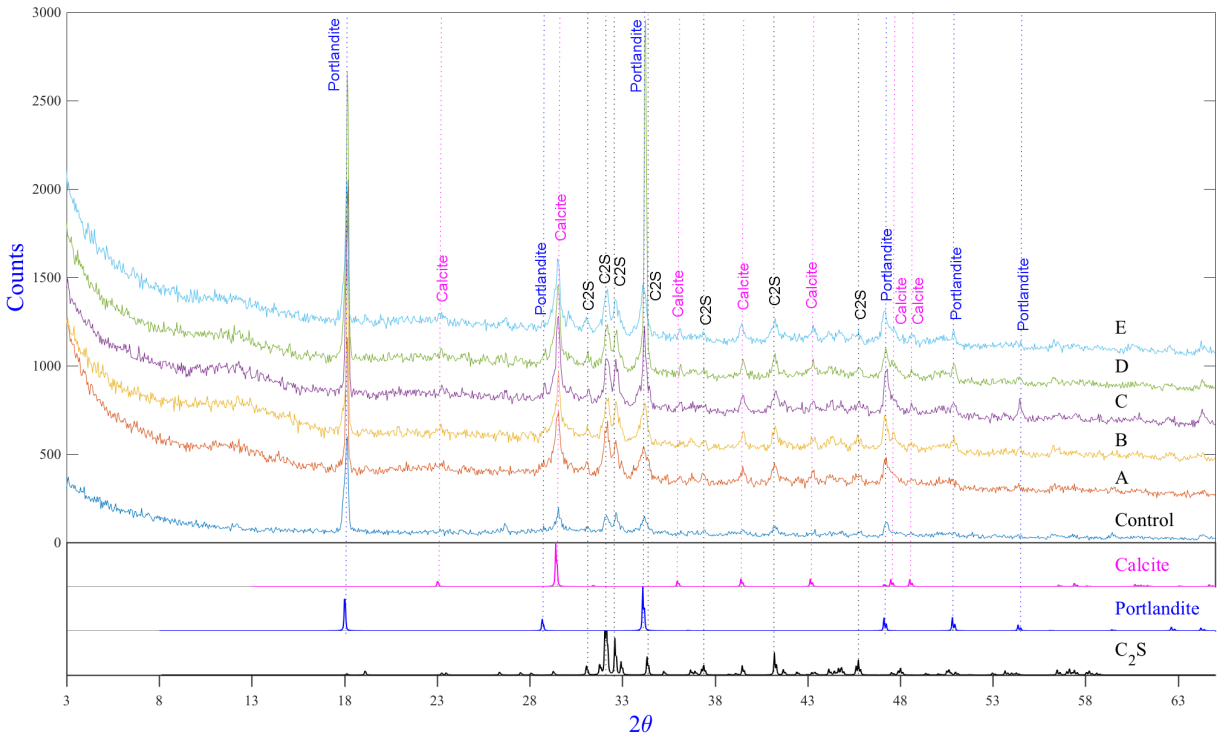

Figure 10: XRD patterns (background subtracted) of biochar-cement samples and control samples after 7 days of curing

Further XRD tests were conducted on biochar samples (size E only) to investigate the change in the chemical composition at different curing time at 7, 28 and 120 days. Table 6 shows a reduction in C_2S over curing time indicating continued hydration and corroborating the strength increase with curing time for biochar samples. There is also a notable increase in calcite content at longer curing periods indicating further carbonation process. Overall, an increasing presence of the main hydration products with curing period could be seen, coupled with a decrease in C_2S, as shown in Figure 11.

4.3 Phase 3 - Effects of biochar quantity

The previous sections have confirmed biochar can be used in replacement for sand and cement as a cheaper and more environmentally friendly alternative. The effects of various combinations of biochar and cement quantities on the strength were investigated on samples cured for 28 days. Four different biochar quantities were tested, 100, 200, 300 and 400 $\mathrm{kg/m^3}$ together with 100, 150 and 200 $\mathrm{kg/m^3}$ cement binder quantity. Only size E (smaller than 75 µm) biochar was used in this experiment as the previous investigation proved it to be the most effective. The results were compared against control samples with 100, 150 and 200 $\mathrm{kg/m^3}$ cement only. It was noted that beyond 400 $\mathrm{kg/m^3}$ of biochar the mixture became dry and difficult to mix evenly.

4.3.1 Results

The results in Figure 12 show that the addition of biochar increased the compressive strength regardless of the amount of cement added. Unsurprisingly, samples with 200 $\mathrm{kg/m^3}$ cement and 400 $\mathrm{kg/m^3}$ biochar were the strongest at 589 kPa. The inclusion of biochar had a more pronounced effect on samples with

Mineral	Control	A	B	C	D	E
Hydration products						
Portlandite (%)	19.9	8.5	9.9	16.7	22.6	13.6
Calcite (%)	12.3	19.0	18.8	17.6	19.2	18.8
$C-S-H$ (%)	16.6	13.5	13.4	15.9	12.3	11.4
Monocarboaluminate (%)	0.0	5.3	5.3	6.4	4.4	6.2
Unreacted cement clinkers						
C_2S (%)	41.1	34	35.2	34.3	28.3	38.1
C_4AF (%)	3.4	11.9	8.4	5.6	9.6	3.0
Other components						
Quartz (%)	3.8	1.2	1.4	0.9	0.8	2.0
Cellulose (%)	0.0	5.0	5.9	2.5	1.6	5.8

Table 5: Results of Rietveld refinement on XRD patterns on biochar enhanced cement stabilised peat with different biochar particle sizes and the control samples at 7 days curing normalised to crystalline fraction.

Mineral	7 days	28 days	120 days
Hydration products			
Portlandite (%)	13.6	5.7	23.2
Calcite (%)	18.8	39.0	32.2
$C-S-H$ (%)	11.4	5.6	9.7
Monocarboaluminate (%)	6.2	8.1	6.3
Unreacted cement clinkers			
C_2S (%)	38.1	24.3	16.0
C_4AF (%)	3.0	4.3	4.9

Table 6: Results of Rietveld refinement on XRD patterns on biochar samples (size E only) at 7, 28 and 120 days curing normalised to crystalline fraction.

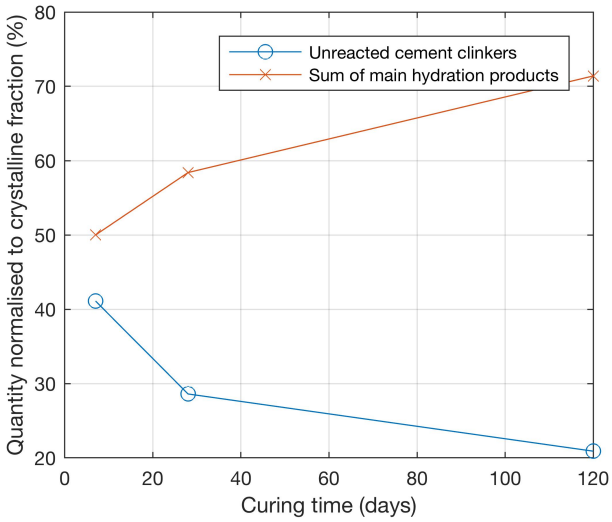

Figure 11: Quantification of Rietveld refinement normalised to crystalline fraction for biochar-cement stabilised peat samples at 7, 28 and 120 days curing

100 $\mathrm{kg/m^3}$ cement with almost 300 % increase in strength from 44 kPa (no biochar) to 174 kPa (400 $\mathrm{kg/m^3}$ biochar). There was less strength gain with increasing cement binder but still respectable with a maximum of 213 % and 195 % increase in strength for samples with 150 and 200 $\mathrm{kg/m^3}$ cement binder quantity respectively. It is interesting to note that samples with 100 $\mathrm{kg/m^3}$ cement binder and 400 $\mathrm{kg/m^3}$ biochar had a compressive strength that is almost comparable with samples with 200 $\mathrm{kg/m^3}$ of cement binder but no biochar. This further justifies the possibility of partial replacement of cement binder with biochar in future peat stabilisation projects.

The dry density of the biochar samples rose steadily with increasing biochar quantity, as expected (Figure 13). Figure 14 shows a steady decline in the water content of the biochar samples with increasing biochar quantity due to the increase in the mass of solids. The information is not sufficient to infer whether the decrease in water content is correlated with increased hydration.

5 Conclusions

The results from this investigation provide strong evidence that biochar can be a successful replacement for sand, especially when biochar fragments introduced into the stabilisation mix are finer than 75 $\mu\mathrm{m}$. Furthermore, the results highlighted the potential for biochar to partially replace cement: biochar samples with 100 $\mathrm{kg/m^3}$ cement and 400 $\mathrm{kg/m^3}$ biochar had strength comparable to the control sample with only 200 $\mathrm{kg/m^3}$ cement, without biochar.

The mechanisms behind the performance gain in biochar samples are both physical and chemical. SEM micrographs indicated that size A to size D biochar samples had biochar fragments with predominantly intact cells, which can potentially become weak zones. However, size E biochar samples (biochar fragments finer than 75 $\mu\mathrm{m}$) had biochar fragments which were too small to show any relict internal cells. The distribution of hydration products in size E samples was noticeably more homogenous. These constituted physical mechanisms improving the performance of biochar samples.

The results from XRD tests showed a notably less C_2S present in biochar samples, indicating that more hydration has occurred. These results constituted chemical mechanisms improving the performance of biochar samples. The results also indicated that the strength of the biochar samples increased with cur-

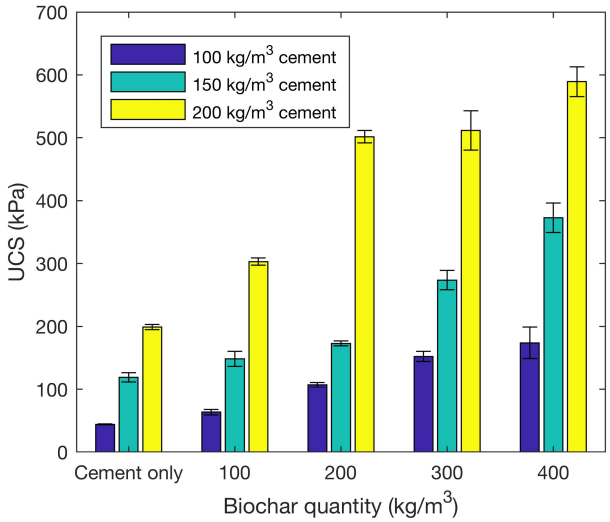

Figure 12: Effects of biochar quantity on UCS of cement stabilised peat with biochar after 28 days of curing

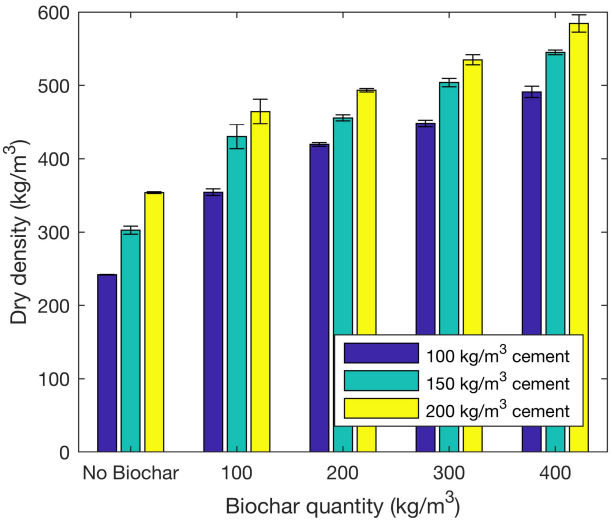

Figure 13: Effects of biochar quantity on dry density of cement stabilised peat with biochar after 28 days of curing

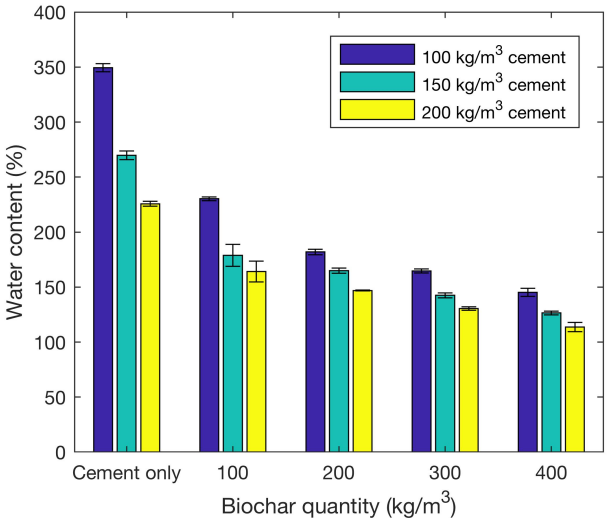

Figure 14: Effects of biochar quantity on water content of cement stabilised peat with biochar after 28 days of curing

ing periods, reaching peak strength at about 28 days curing. The results from XRD tests corroborated this observation with a further reduction in C_2S with curing time.

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